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Decrease in heliospheric magnetic flux in this solar minimum: Recent Ulysses magnetic field observations

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[1] The Ulysses spacecraft has traveled from the solar equator at 1.3 and 5.3 AU to above the polar caps at 2.2 AU three times during the last 17 years and has provided measurements of the solar–heliospheric magnetic field. The open magnetic flux, i.e., the radial component, B_R, multiplied by the square of the radial distance, r, is independent of latitude at both solar minimum and maximum. Measurements of r^2 B_R contain information about the average polar cap field strength when allowance is made for the non-radial expansion of the magnetic field and solar wind near the Sun that eliminates the latitude gradient in magnetic pressure. Recent Earth-based magnetograph observations indicate that the Sun's polar cap field strength, B_P, has decreased by a factor of about two between the previous and present latitude scans. Ulysses measurements show that the average value of r^2 B_R has decreased from 3.6 nT $(AU)^2$ in 1993.5 to 1995.0 to 2.3 nT $(AU)^2$ in 2006.1 to 2007.4, a decrease by 0.64. The two Ulysses scans are not precisely at solar minimum. However, in-ecliptic B_R is highly correlated with the Ulysses measurements at all latitudes and can be used to determine the open flux at the two solar minima. Averages of B_R at the two solar minima are 2.82 and 2.45 nT. This decrease is contrary to the suggestion based on previous solar cycles that B_R returns to the same value of $\approx$ 3 nT at solar minimum. The ratio of B_P to the expansion factor, f_E, is proportional to the measured open flux and observed and assumed values of B_P are used to determine the corresponding values of f_E. Another property of the fast solar wind is that it is highly turbulent compared to lower latitudes. To determine if the decrease in r^2 B_R and B_P has affected the intensity of the magnetic fluctuations, the total variances in the magnetic field fluctuations are derived and found to decrease by a factor of 0.75. **Citation:** Smith, E. J., and A. Balogh (2008), Decrease in heliospheric magnetic flux in this solar minimum: Recent Ulysses magnetic field observations, *Geophys. Res. Lett.*, *35*, L22103, doi:10.1029/2008GL035345.

1. Introduction

[2] A major objective of the Ulysses magnetic field investigation has been the measurement of the Sun's polar cap magnetic fields and a comparison with estimates of the field strength obtained by magnetographs. The initial expectation was that measurements as a function of latitude would reveal by how much the heliospheric magnetic field (HMF) strength increased from the equator to the pole. The parameter of greatest interest is the radial component, B_R, because, as the Parker model of the HMF [*Parker*, 1963] shows, r^2 B_R is invariant along a field line so that B_R at the Sun can be derived from measurements of B_R inside the heliosphere at radial distance, r. On the other hand, the longitudinal component and the field magnitude depend on the solar wind speed, the rotation rate of the Sun and helio-latitude. In the Parker model, the field lines are "open" with one end attached to the rotating Sun and the field extending into space along an Archimedes spiral.

[3] Surprisingly, Ulysses measurements of B_R are independent of latitude at both solar minimum and solar maximum [*Smith and Balogh*, 1995, 2003]. Implications are that the field and solar wind are expanding non-radially from high to low latitudes, that the expansion is driven by magnetic field pressure rather than solar wind plasma pressure and that measurements of B_R at any latitude are a measure of the total open heliospheric magnetic flux [*Smith and Balogh*, 1995]. Furthermore, extrapolation of B_R back to the Sun must include the effect of the non-radial expansion. The latter has been derived, for example, from the measured r^2 B_R [*Banaszkiewicz et al.*, 1998] and from potential field source surface models [*Wang and Sheeley*, 1990].

[4] Measurements of r^2 B_R are available from two Ulysses latitude scans in the fast solar wind near solar minimum, 1993.5 to 1995.0 and 2006.1 to 2007.4. Measurements near sunspot minimum are of particular interest because the Sun's dipole magnetic field is strong even though solar activity is low. Comparison of the r^2 B_R measurements in the two epochs is scientifically compelling because, following the polar field reversal in 2000–2002 and its subsequent reestablishment, magnetograph measurements indicate that the field strength decreased by a factor of about two (Stanford University, http://wso.stanford.edu). Furthermore, in the past three solar minima, in-ecliptic measurements of B_R have returned to essentially the same value or "floor" suggesting that the minimum open flux is invariant [*Svalgaard and Cliver*, 2007].

[5] In the following, the open flux measured by Ulysses near this and the previous solar minimum are compared and used to derive values of the polar cap field strength and the solar wind expansion factor. The high degree of correlation between r^2 B_R and in-ecliptic B_R is used to obtain measurements of open flux precisely at the two solar minima so that they can also be compared. Finally, another property of the fast high latitude wind is investigated that might be related

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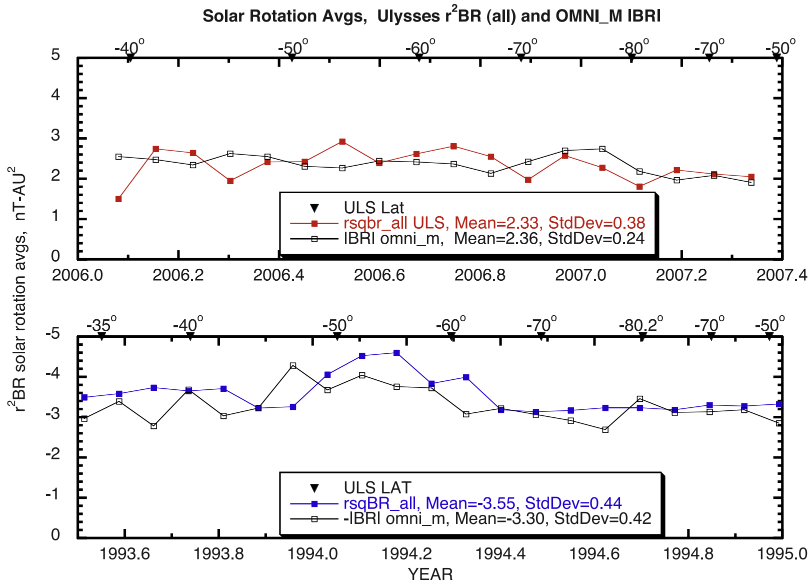

Figure 1. Ulysses r^2 B_R and Omni B_R: Comparison at high latitudes and in the ecliptic simultaneously and near two solar minima. The two plots contain 27-day averages of r^2 B_R at Ulysses (red) and in -ecliptic B_R (black) for the two intervals when Ulysses was in the fast solar wind at high latitudes. (top) Data obtained in 2006.0–2007.4 during the current solar minimum while Ulysses traveled from $-40°$, under the south pole and back to $-50°$ (latitude appears along the top scale). The means and standard deviations show that there was no statistically significant difference in the high and low latitude measurements and no evidence of a latitude gradient. (bottom) Same format but r^2 B_R is plotted in blue and the interval covered is 1993.5 to 1995 during the previous solar minimum. Again, there is no evidence of a latitude gradient in r^2 B_R but the means show a decrease compared to Figure 1 (top).

to B_P and its decrease, namely, the strong turbulence as measured by the total variance in the magnetic field fluctuations.

2. Observations

[6] In Figure 1, r^2 B_R, is plotted as a function of time during the recent solar minimum (Figure 1(top)) and during 1993.5–1995.0 (Figure 1(bottom)). The solid squares are solar rotation averages of r^2 B_R at Ulysses and the open squares are corresponding solar rotation averages of B_R in the ecliptic obtained from the Omni data site at the National Space Science Data Center (http://nssdcftp.gsfc.nasa.gov). The units are nT $(AU)^2$ and nT, respectively. The standard errors in the averages, the standard deviation divided by the square root of the number of hourly averages in each solar rotation, are all comparable to the size of the symbols used to display the averages. The inclusion of the Omni data allows the separation of temporal from spatial variations. Heliographic latitude is shown along the top scales of the two panels. The latitude ranges cover intervals when Ulysses was immersed in the fast solar wind from the polar caps.

[7] The upper panel again reveals the absence of a statistically significant latitude gradient. Comparison with the in-ecliptic data shows that time variations, including any long- term trend, were small enough not to confuse time and spatial variations. The means and standard deviations of 2.33 ± 0.38 and 2.36 ± 0.24 indicate that there is no significant difference between r^2 B_R at high latitudes and B_R in the ecliptic.

[8] In the lower panel, a temporal change occurs at Ulysses and also in the ecliptic beginning before the last half of 1994. However, the changes are nearly identical again implying the absence of a spatial gradient. The means and standard deviations, 3.55 ± 0.44 and 3.30 ± 0.42, are the same within statistical uncertainty.

[9] We conclude that the average value of r^2 B_R has decreased from 3.6 in 1993.5–1995 to 2.3 in 2006–2007, a decrease of 1.3 nT $(AU)^2$ or by a factor of 0.64. This decrease is similar to the decrease in the polar cap field by a factor of approximately 0.5 inferred from magnetograph observations.

[10] Based on the Parker model, a similar decrease would be expected in the field magnitude. Since, $B^2 = B_R^2\,(1+ (\Omega r \sin\,\theta/V)^2)$ and the solar rotation frequency, Ω, the co-latitude,θ, and the solar wind speed, V, are basically unchanged, B should be proportional to B_R and also decrease by a factor of 0.64. In fact, plots of measured B at Ulysses vs. latitude (not included here) follow the Parker relation fairly closely and show the anticipated decrease in B between the two solar minima.

[11] To show the decrease in B_R and B at this solar minimum as compared to the past, the radial component and field strength in the ecliptic are plotted in Figure 2 over an extended time interval. The symbol, B_R (+, −) indicates that B_R was averaged in each magnetic sector separately and then differenced to provide an accurate estimate of B_R magnitude. The short horizontal bars indicate when the two Ulysses latitude scans took place. The decrease from the first to the second scan is evident in both B_R and B.

[12] Smoothed Sunspot Numbers (SSN) are added to Figure 2 to identify successive solar minima and their relation to the Ulysses data intervals. The first scan actually occurred prior to the solar minimum in 1996 and during the

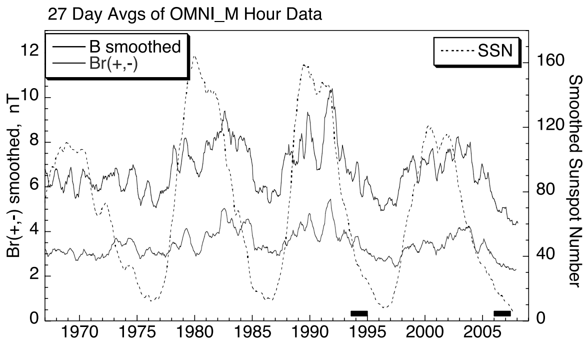

Figure 2. Omni B_R and B for four solar minima. The data are smoothed 27-day averages between 1965 and 2008 and follow the 11-year solar cycle shown by the Smoothed Sunspot Numbers. The first significant decreases are observed at the solar minimum in 1976. Both B_R and B decrease in subsequent minima in 1986 and 1996 and return to about the same values. The data in 2006–2007 show the recent significant decreases in field strength and open flux.

declining phase. The recent data were acquired very near but not precisely at the present solar minimum (the SSN show that we are now at or very near solar minimum).

[13] Since in-ecliptic B_R is so well correlated with r^2 B_R, it can be used to determine the open flux at this minimum compared to the minimum in 1996. The annual average of B_R (+, −) is 2.82 nT in 1995–1996 and 2.45 nT in 2006–2007, a decrease by 0.87. Actually, both averages are significantly less than the corresponding values at the minima in 1976 and 1986 that are closer to 3 nT.

[14] The decrease of the field strength in the fast wind raises the question as to what other aspects of the magnetic field may have changed. The fast high latitude solar wind is characterized by persistent large amplitude magnetic fluctuations, principally Alfven waves [*Smith et al.*, 1997; *Horbury and Tsurutani*, 2001]. Therefore, the variances in the field fluctuations in 2006–2007 have been compared with those in 1993.5–1995 to see if a change has occurred.

[15] In Figure 3, the total variances, i.e., the sum of the variances in the radial, longitudinal and latitudinal components (in nT^2) are averaged over a solar rotation and plotted as a function of radial distance (for convenience only, ignoring a possible latitude dependence). The equations for best fit power laws are shown along with the best fit straight- lines. The very large correlation coefficients are shown. Since the variances fit an r^{-1} dependence, the values at 1 AU are representative of an overall decrease. At 1 AU, the total variance is 2.86 in 2006–2007 and 3.82 in 1993–1995, a decrease by a factor of 0.75.

[16] Although no simple physical connection of the magnetic fluctuations with B_R or B has yet been established, the variances have also responded to the change in the background field. The correlation may contain information about the origin and evolution of the fluctuations near the Sun, in the solar wind or both.

3. Discussion

[17] The recent latitude scan shows that r^2 B_R has undergone a significant decrease as compared to Ulysses measurements near the previous solar minimum. In-ecliptic values of B_R and B show the same decrease and are significantly lower at the two recent solar minima than in the three previous minima (1976, 1986 and 1996) when B and B_R returned to nearly the same value and it was speculated that the amount of the minimum open flux is invariant [*Svalgaard and Cliver*, 2007]. However, this solar minimum, the polar cap field and the open flux both decreased significantly providing further evidence that they are closely related.

[18] Flux conservation relates the total open flux, Φ, to the polar cap magnetic field, B_p. In terms of the photospheric radius, r_p, and the co-latitude, θ, $\Phi = \int\int B_p\, r_p^2 \sin\theta\, d\theta\, d\phi$. If B_p changes only slightly in the polar cap and can be considered uniform, $\Phi = B_P\, r_P^2\, \Omega_P$ where the solid angle occupied by the polar cap, $\Omega_P = \int\int \sin\theta\, d\theta\, d\phi$. If polar cap B_p varies with latitude and longitude, the average value becomes $\langle B_p\rangle = \int\int B_p \sin\theta\, d\theta\, d\phi/\Omega_P$ and $\Phi = \langle B_p\rangle\, r_P^2\, \Omega_P$.

[19] At the Source Surface, $\Phi = \int\int B_{SS}\, r^2_{SS} \sin\theta\, d\theta\, d\phi = B_{SS}\, r^2_{SS}\, \Omega_{SS}$ in terms of the solid angle occupied by the flux from the polar cap as distributed on the source surface. Similarly, at Ulysses, $\Phi = B_R\, r^2\, \Omega_{SS}$ since the flow outward from the source surface is radial and the solid angle at Ulysses is also Ω_{SS}. The relation between r^2 B_R and B_p becomes $B_p = r^2\, B_R\, \Omega_{SS}/r_p^2\, \Omega_P = (r/r_p)^2\, B_R\, f_E$ where the expansion factor $f_E = \Omega_{SS}/\Omega_P$. Thus, the observed value of r^2 $B_R = r_p^2\, B_p/f_E$. A decrease of 0.64 means a decrease in B_p/f_E by the same ratio. If B_p has decreased by 2, f_E has decreased by 0.78. If B_p is known or assumed, f_E can be calculated, e.g, B_p = 5 gauss and r^2 B_R = 3.4 nT(AU)^2 implies f_E = 3.15 whereas for B_p = 2.5 gauss and r^2 B_R =

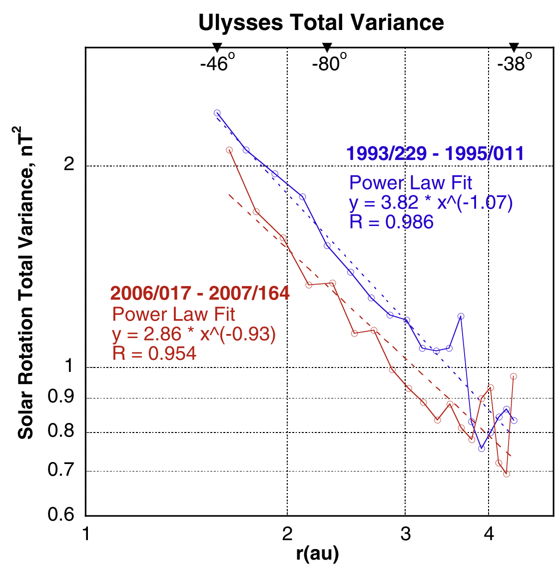

Figure 3. Total variances, σ^2, at Ulysses during the two high latitude scans near the two more recent solar minima. The three variances of the radial, longitudinal and latitudinal field components (in nT) have been summed to yield the total variance, or power in the field fluctuations, then averaged over 27-day intervals and plotted as a function of radial distance, r. The upper (blue) data refer to the earlier epoch and the least squares linear fit is shown. The lower (red) data were obtained in the recent scan and the straight-line fit is also shown. A significant decrease is evident in the recent observations.

2.3 nT(AU)^2, f_E = 2.33. A decrease in B_p is accompanied by a decrease in f_E as would be expected if the expansion is driven by magnetic pressure in the polar cap. Actually, in 1993.5 to 1995.0, the average polar field strength based on measurements of four Earth-based magnetographs was 9 +/1.5 gauss [*Arge et al.*, 2002] implying f_E = 5.7. Assuming a decrease in 2006–2007 by a factor of two, f_E = 4.2.

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